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An Integrated Approach Towards Sustainable Manufacturing – A Framework

Khir Harun[1], Idrus Moin[2], Harridon Suffian[3], Noraida Abd Rahman[4], Nor Hisyam Ghafar[5], Fakhrulnizam Mohamed[6]
[1,2,3,4,5,6] Universiti Kuala Lumpur - Malaysian Institute of Aviation Technology, Malaysia.
[*]Corresponding author: mdkhir@unikl.edu.my

Abstract. Manufacturing systems can be a very challenging due to impact of processes complexity, by-products and extensive energy consumption in production prior to a product realization. For these reasons, the aims of this research is to develop manufacturing processes/systems that focus not only on costs and delivery time, but also environmental burden during production. Life Cycle Analysis (LCA) has been re-visited whereby Inventory Analysis (IA) is systematically assessed using IDEF0 activity modelling technique with simulation-oriented based software. The methods form as a structured integrated hierarchical approach to process implementation for sustainable manufacturing. Using simulated manufacturing process, the results have shown that each process can be clearly differentiated in the perspective of energy consumption, cost and also by-products. The results not only allows for the identification of steps with potential optimization of material and energy input, but also help to discover important area for future process improvement. The evaluation of results help to support decision making during process design configurations where economic, environmental and technological perspectives are considered to support sustainable manufacturing system.

Keywords: IDEF0, sustainability, simulation, automotive painting process, automotive manufacturing, life-cycle assessment

1 INTRODUCTION

As the world faces ever-increasing environmental challenges, the demand for solutions is growing and pressure is being aimed at business enterprises to provide an answer. In this dynamic and complex global environment any new models should not only focus on the innovation of critical manufacturing processes, but also requires multidisciplinary scientific expertise with practical tools and solutions. The aim is to support the knowledge-based eco-engineering of complex manufacturing processes and to foster the use of advanced sustainable technologies within the organization. Greener and more resource-efficient production in manufacturing implies the application of holistic environmental protection strategies to manufacturing processes by continuously reducing environmental pollution (Willard 2002). For this reason, mass and energy balances play important elements as a basis for the environmental classification of processes and for comparing products or production processes. Therefore, any improvement goal should not only focus on pure description and comparison but to allow for environmental sound design of production processes which can be achieved through systematic evaluation of manufacturing processes and systems. Current simulation softwares do not typically support the modeling of environmental concerns or impacts, for example, energy consumption or waste materials disposal. Typical manufacturing processes do not consider the types and quantities of manufacturing waste. Simulations typically do not model the by-products of manufacturing, generation of effluents, or their disposal. Information on alternative manufacturing technologies, processes, and data is not readily available to the simulation analyst to incorporate into models. Consequently this brings on the focus for simultaneous process simulation and modelling within process LCA to design and develop new manufacturing processes.

According to Ramani *et al*. (2010) most eco-design tools fall into 3 categories (a) tools based checklist (b) tools based on life cycle assessment (LCA) and (c) tools based on quality function deployment. As a result, numerous tools under these categories have been proposed and developed, for examples, Choi and Ramani (2009), Koffler *et al*.(2008), Yu *et al*. (2001), Devanathan (2010), Luttropp and Lagerstedt (2006), Lee and Park (2005), Masui *et al.* (2003); Bouchereau and Rowlands (2000). There were also efforts to develop a more holistic approach to the design process including web-based framework (Lofthouse 2005), integrating various technologies such as life cycle simulation (Harsch 2000), and multi-criteria decision making (Sadiq and Khan 2004). Although these works contributed significantly in the selection of tools for sustainable manufacturing design, shortcomings remain. First, phases of process design are not considered on the entirety (top-down approach) of the business point of view. The IDEF-based models/modeling of business process, typically called activity models/modeling can be a good choice to clarify relations of activities (Ball 2008; Fushino, 2003). IDEF0 is one of such tools that can be exploited due to its simplicity but can be very powerful to represent the holistic approach in any process flows of the manufacturing processes. Secondly, a "snap shot" character of Life-Cycle Inventories (LCI) is not flexible to enable predictions about product and technology development. Therefore, simulation studies are often conducted to analyze and improve the efficiency and effectiveness of some aspect(s) of a manufacturing system. There is very little research publication where manufacturing simulation includes environmental problems or parameters in the modeling process.

In this research we proposed a systematic integrated process design incorporating LCA related activities for the assessment and simulation of the cause and effect of various process/systems. Using the developed process algorithm using commercially available software and IDEF0 methodologies we investigate the feasibility in the real life environment. The proposal also serves as a blueprint for a business model enabling timely decision making for complex activities which can be applied in any process related industries.

2 THE DEVELOPMENT OF PROPOSED METHODOLOGY

In responding to current challenges, manufacturing enterprises need to re-look at their present organizations' strategies, systems and processes for improvement. Selecting tools for details assessment can be very challenging as there are many aspects or initiatives such as design for experiment, re-manufacturing, re-cycle, reduction of emissions, health and occupational safety that need to be considered to achieve objectives and goals for environmentally friendly design (Hong *et al.* 1997, Westkamper *et al*. 2000, White *et al*. 2003, Hauschild *et al*. 2004, Winifred *et al*. 2007). In addition, there are numerous categories of tools and methods using integrated assessment which can be used for supporting decisions related to policy or project specific from local to global scale assessment (Ness *et. al*. 2007). As illustrated in Fig.1, a potential subset derived from the *synergy*, enterprises should consider design their processes/products concurrently based on comprehensive but structured integration of manufacturing strategies, production processes & systems and product life cycle in order to be considered as sustainable, without destroying precious resources or the environment. These components should not be considered in isolation but should be designed in an integrated manner.

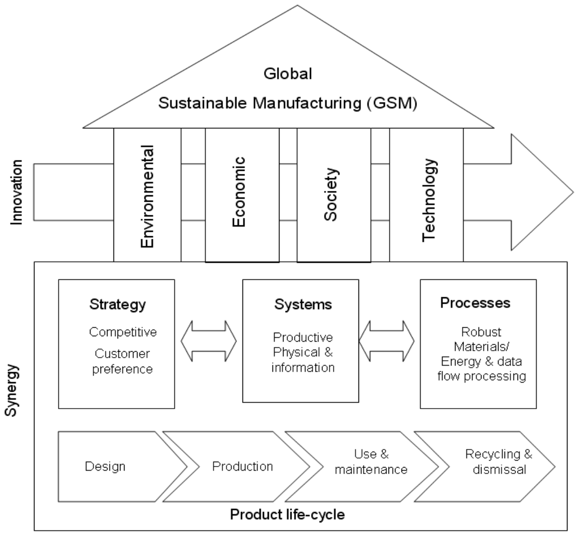

Fig. 1 System approach for Sustainable Manufacturing (SM)

2.1 Selection of software tools

IDEF0 is a hierarchical activity-based modelling method developed for modelling functions of complex but interrelated systems. It was derived from a well-established graphical language known as structural analysis and design technique (SADT) and subsequently refined version known as IDEF developed by the U. S. Air Force for defining complex set of interacting activities involved in the life cycle of an aircraft. Activity modelling is one effective approach and widely acceptable for describing the whole procedure as a business model. It is the most effective way to communicate with technical and non-technical people, including management, as it plays a vital role in bridging the communication gap between these two groups (Feldman 1998). Activities may be transformation, movement, generation, use, or disposal of material, energy, or data and information. Activity Modelling is the process of defining each activity (function, operation, process, *etc.)* in a system which involves several inter-linked sub-activities. An integrated model view can capture the complexity and interaction of a system to enable it to be easily understood. The static representation of the system can help in identifying various activities and interlinking of these activities can be traced to material, energy and waste flows associated with each activity that form the inputs of another (Ball 2008).

Simulation has been demonstrated to be a very effective approach for problem solving and optimizing manufacturing systems design. Simulation-oriented process design has been used for numerous purposes, such as product flows in manufacturing, military strategies, logistics and in the design phase to evaluate concepts and optimize system solutions before investment decisions are made (Law and McComas 1999). Using simulation and a formalized language between the agents, a batch process for the manufacture and supply of materials can be modelled and design implications can be identified, which highlight agile structures for a competitive advantage (Garcı´a-Flores and Wang 2002). Scenarios for different process alternatives can now be investigated in order to decide the best alternative solution(s). While industrial modeling with LCA describes static models, simulation offers “what-if” scenarios capable of analyzing alternative models to reflect how the systems work in comparison to others. The integration of LCA and simulation-based process is feasible and has potential to contribute towards the wealth of knowledge in sustainable manufacturing process. Table 1 highlights ideal characteristics of selected tools that are considered in this study for the benefit of decision makers, for example, production engineer or production planning designer working on either modifying an existing or designing a new manufacturing processes or systems.

Table 1 Selection of tools with preferred features (highlighted in italics)

FEATURE	IDEF0	LCA	SIMULATION
Dynamic assessment	Deterministic, standard or average parameter	Deterministic, standard or average parameter	***Dynamic event, probabilistic parameters***
Data availability		***Public LCA data available***	
Visualization	2D process map	Limited process view	***3D visualization and animation***
Simplified	***Hiearchical top-down tool, user friendly***	Experts tool	Experts tool
Standardization	Widely used in industry for business process re-engineering	***Standard ISO 14040-14044***	Partially
Framework for environmental impact analysis	Development of methodology has been presented	***The main tool***	Mostly research driven, also commercial solution entering the market

2.2 Tools Integration Methods

The key for integration methodology of LCA and simulation-based is the sharing of evaluation indexes to each methodology through matched features of the evaluation indicators and the actual impacts after the appropriate each alternative process evaluation as shown in the developed activity model. The model characteristics are integrated through determination of combined objectives, a comprehensive interpretation, and information sharing in both methods. In the definition of scope and setting and interpretation, information is shared to avoid the setting of redundant evaluation indexes and ineffective interpretation. Extensive interpretation requires the judgment to eliminate options and decide alternatives on the basis of the meanings of evaluation results.

The relevancy of assessment assignment can be checked in the execution activities of each assessment, and the request to change the evaluation settings can be fed back to the activity as the concept *feedback information*. The objective settings and the interpretation of evaluation results are linked through the first management activity, which enables the re-definition of evaluation strategies by modifying the internal constraint on the basis of the feedback information from interpretation activities. These activities are accomplished by the developed activity models. The software tool selected is the GaBi4 software system due to its versatility. The design of the facilities/processes can be modelled according to the material and energy flow. All boundary conditions e.g., efficiency, time of operation, climatic boundary conditions, emissions to air, water and soil can be modelled as parameters. This enables the user to run simulations with different boundary conditions using the base model with different configurations for all scenarios of interest.

2.3 The Proposed Framework

As shown in Fig. 2, the objective was to integrate the LCA process modelling approach with LCA in order to improve the way of assessing the life cycle impact analysis (LCIA) for production variables. A generic framework that describes an approach to develop eco-friendly and compliant products based on technical, environment and economic considerations. The approach consists of two phases: (1) integration phase and (2) life cycle applications phase and the relationships between them. The “integration” phase comprised of structure and process that are linked using activity modelling technique, IDEF0.

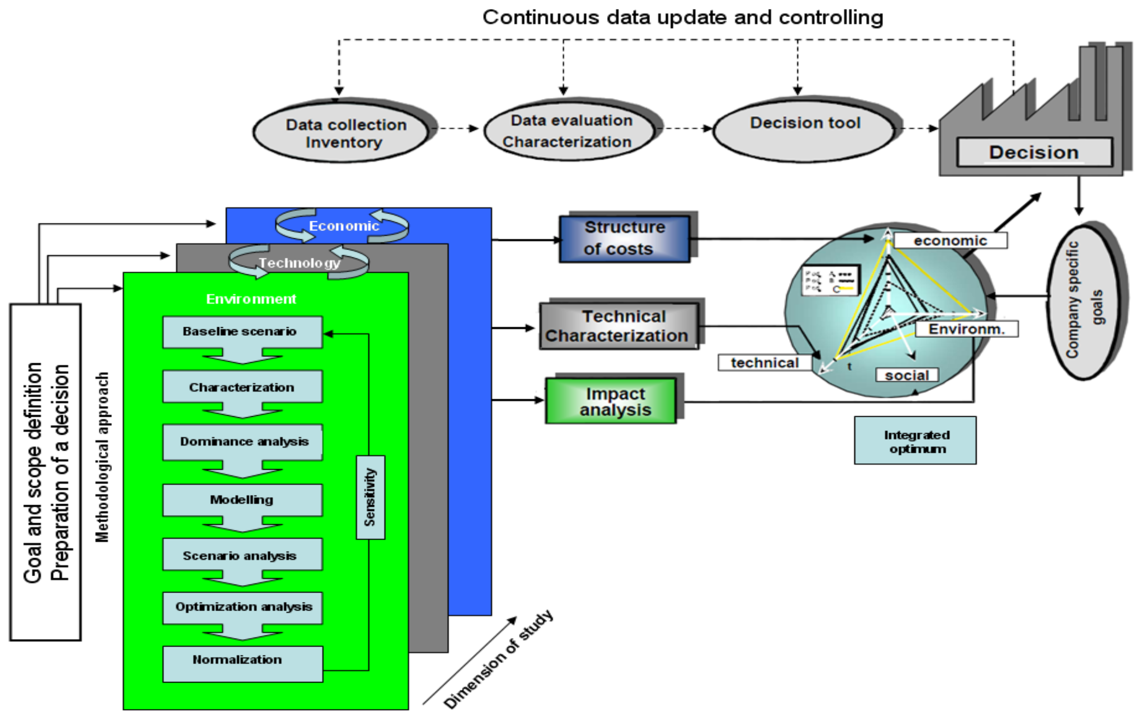

Fig. 2 The Proposed Framework

The framework is made up of 4 key parameters - ‘structure’, ‘process’, ‘organization’ and ‘simulation & analysis’. The ‘structure’ consists of functional modelling and dominance analysis. The ‘organization’ parameter is where the “top-down” business process approach using IDEF0 technique where diverse related information and activities are linked together. Such activity modelling will be presented as necessary with details of decomposition and aggregation of systems. The ‘process’ contains all information on processes which may include product manufacturing processes, raw material processing, LCI, etc. Although this can be expanded in the future to include quality, legislations, etc. This study scope is limited to “cradle-to-gate” manufacturing process only. Cradle-to-gate includes all processes from the raw material extraction through the production phase (gate of the factory); used to determine the environmental impact of the production of a product.

Within the life cycle application phase, ‘simulation & analysis’ summarizes all life cycle applications such as Life cycle cost (LCC), technology or other parameters, if any. The software, GaBi4 is chosen to perform the modelling and balancing. It is all-in-one software tool developed capable of modelling products and systems from a life cycle perspective. Modelling of material and energy inputs and outputs including emissions are constructed. With a modular and parameterized architecture, the software allows rapid modeling even of complex processes and different production options and also capable of adding other data such as economic cost or social impact information to a model, making GaBi a holistic life cycle analysis tool.

Finally, this framework needs to consider a product environmental impact on the entire life cycle phases and the optimization with regard to technical, economic and environmental. As product/process development was normally considered as an interdisciplinary multi-constraint decision process whese issues however had to be solved by multi-criteria optimization (MCO) method, the goal programming. So a holistic life cycle concept covering a product life from raw materials to production processes or cradle-to-gate has been defined.

2.4 Implementation

Preliminary implementation is proposed on automotive manufacturing where data is currently available for the purpose of this research. The automotive painting or coating process is a complex, multistage operation that is extremely energy intensive and also the primary source for air emissions (Fig 3). The painting process is also a major cost of production, with large capital investments and high material costs. Specific costs for automotive paint materials vary depending on the exact chemical formulation, the colour, and the application process used. In general, coating materials represent about half the cost of painting the vehicle (Nallicheri 1993).

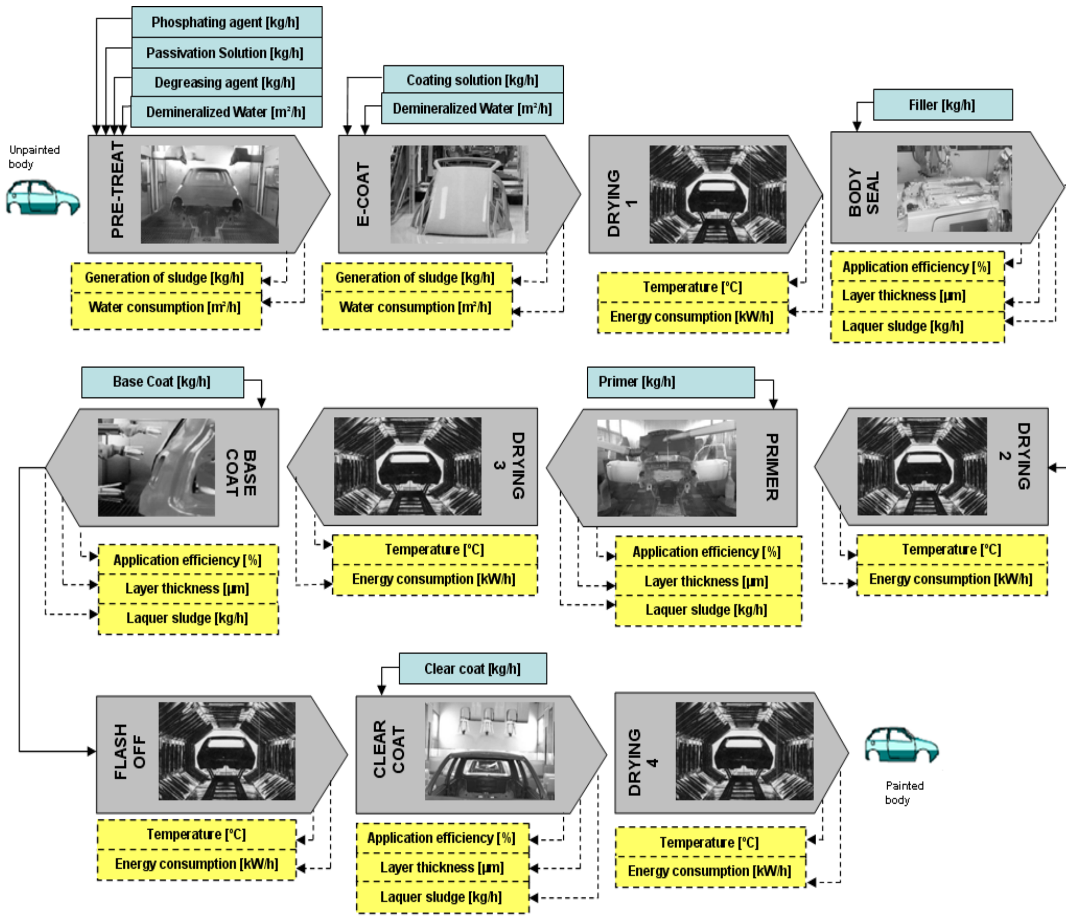

Fig. 3 Typical stages of automotive painting process

3 CONCLUSION

In this paper we presented an integrated simulation based LCA. This activity model was also developed to act as business model template in manufacturing process design. Each step of the framework are supported with appropriate tools and required information that can be explicitly defined and implemented. The benefit of adopting activity modelling technique worth mentioned here is the hierarchical description of the entire business activities. The proposed modelling framework were developed using commercially on-the-shelf software tool which is proven to be effective and useful. The parallel consideration of the modelling techniques using IDEF0 with LCA and scenario based simulation allow not only identification of steps with potential optimization concerning material and energy input, but also help to discover important area for future study. The assessment exercise should generate potential process that can be considered where the impact of economic, environmental and technical dimensions which can provide different perspective for sustainable manufacturing.

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